Renewable and Sustainable Energy Reviews 16 (2012) 4148–4156

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Experimental comparison of impact of auction format on carbon allowance market

Rong-Gang Cong[a,b,*], Yi-Ming Wei[c,d]

[a] School of Economics and Management, North China Electric Power University, Beijing, 102206, China
[b] Centre for Environmental and Climate Research (CEC), Lund University, Lund, 223 62, Sweden
[c] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing, 100081, China
[d] School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China

ARTICLE INFO

Article history:
Received 28 December 2011
Accepted 16 March 2012
Available online 30 April 2012

Keywords:
Allowance allocation
Auctions
Experimental economics
Carbon emissions trading
Explicit collusion
Tacit collusion

ABSTRACT

Carbon allowances auctions are a good way to achieve the carbon allowance allocations under international agreements to address global climate change. Based on an economic experiment, this paper compares three possible carbon allowance auction formats (uniform price auction, discriminatory price auction and English clock auction) with heterogeneous bidders (coal power plants and gas power plants) from four perspectives (carbon price, auction efficiency, demand withholding and fluctuations in power supplies). Possibilities of collusion among bidders and impacts of allowance banking and penalty price on bidders' behaviors under different auction formats are also examined. The results show that (1) when there are relatively more bidders and there are no obvious communications between them, despite there being some tacit collusion, efficiency of English clock auction is greater than the other two formats; (2) when there are relatively fewer bidders and there are obvious communications between them, explicit collusions are observed under English clock auction. In this case, discriminatory price auction helps prevent collusion to some extents; (3) in the banking scenario, more speculations are observed, while penalty price exacerbates price volatility.

Contents

1. Introduction

As emissions of carbon dioxide and other greenhouse gases are growing, various mechanisms for emission abatement are receiving widespread attention from governments and scholars. To help signatory states achieve emissions reduction in a cost-effective

* Corresponding author at: School of Economics and Management, North China Electric Power University, Beijing, 102206, China. Tel.: +86 13811649984.
E-mail address: cascong@126.com (R.-G. Cong).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2012.03.049

way, the "Kyoto Protocol" introduced three flexible mechanisms, which are emissions trading (ET), joint implementation mechanism (JI) and clean development mechanism (CDM). In ET, allocation of initial allowances to industries or equipment which emit pollutants is a very important issue [1]. The initial allocation of carbon emission allowances is the basis of designing the ET mechanism. Free allocation by government, auction and a combination of the two are the main allocation modes suggested by scholars [2].

Compared with free allocation, auction can allocate allowances to the agents who need them most. Auction revenues can also be used to finance environment protection measures for addressing climate change and to reduce distortions of the relevant tax. Therefore, it is more appropriate to auction carbon allowances due to the "double dividend" effect [3]. In theory, agents can achieve emissions reduction at a low cost on the whole [4].

The largest carbon trading market – European union emissions trading system (EU ETS) – is currently employing a combination of free allocation by government and auction. EU countries were allowed to auction up to 5% of overall emissions rights in the first phase (2005–2007), and auction up to 10% of overall emissions rights in the second phase (2008–2012). The rest are allocated free by governments.

However, there are still many issues to be further studied. For example, which format should be chosen for multi-units carbon auction? What about the possibilities of collusion between bidders in different auction formats? What is the impact of banking and penalties for bidders' behaviors? How can these factors be analyzed in an integrated framework, and how can results from different experiments be compared are also the focus of this paper.

The results may shed light on the impact of auction on the bidders' behaviors and even potentially cause a change in China's environmental policy. Also, some conclusions may be useful for laying down the general rules of the carbon market, which may be a contribution to existing literatures. The article is structured as follows. Section 2 introduces literature relating to the carbon auction mechanism and economics. Section 3 is devoted to illustrating the experimental design in general. Section 4 contains results of the experiment, and Section 5 concludes.

2. Literature review

There are two types of auctions, static (sealed) auction and dynamic (clock) auction. Static auction can be further divided into uniform price auction, discriminatory price auction and second price auction, according to the different market clearing price, as shown in Table 1.

Selecting the optimal type of auction has been a matter of debate for researchers and governments. Klemperer argued that a good auction mechanism should be able to prevent bidders from colluding with each other [5]. Tacit or explicit collusions may produce significant impact under different auction mechanisms [6,7]. Pekec and Tsetlin compared discriminatory price auction and uniform price auction and found that compared with uniform price auction, discriminatory price auction allows the auctioneer to get more revenue in the presence of uncertainty about the number of participating bidders [8]. Based on an economic experiment, Alsemgeest et al., compared English clock auction and sealed uniform price auction [9]. They found that when communications between bidders were prohibited and market clearing price was announced after each round of auction, sealed uniform price raised more revenue for the auctioneer than English clock auction, which means bidders found it easier to collude under English clock auction. Burtraw et al. believed that due to decisions on only one-dimension (bid quantity) rather than two-dimensions, bidders are more likely to collude under clock auction [10]. They also found that discriminatory and uniform price auctions produce greater revenues than the clock auction, both with and without explicit communication. Goeree et al. reported a multi-unit auction to evaluate the possibility of demand withholding in the case of no communications [11]. They found that the auctioneer's revenue under discriminatory price auction was much larger than in ascending clock auction. Demand withholding under ascending clock auction was more significant. Katok and Roth compared two clock auctions of multi-unit homogeneous goods [12]. They found that descending auction should be adopted in mature markets, while ascending auction is more suitable for emerging markets.

Different types of auctions have been compared extensively in extant literature, but their conclusions are not uniform. Also comparisons in the context of carbon auctions are relatively few. A significant feature of carbon auction is that bidders can bank their unused allowances for future use. Banking makes intertemporal bidders' abatement costs verge to equal, which provides flexibility of emissions abatement and reduces the corresponding costs [13]. Cronshaw and Brown designed an experiment for allowance market under the US clean air act of 1990 [14]. They found that in theory, banking increased revenue of auctioneer by about two third. Experiments by Godby et al. and Mestelman et al. also showed banking could help smooth allowances' price [15,16]. Cong and Wei established a multi-agent model to study uniform price auction and discriminatory price auction from four aspects (the relationship between demand and supply, uncertainty of generation cost, bidders' learning abilities and market structure) [17]. It was found that discriminatory price auction was better from the perspective of efficiency, while uniform price auction was better in terms of fairness which is good for small agents.

Because different bidders have different risk preferences, utility of the same revenue may be different for them, which may also affect bidders' behaviors. Chen et al. compared uniform price auction and discriminatory auction based on bidders' risk preferences [18]. They found that when bidders were risk averse, discriminatory price auction could raise more revenue for auctioneer; when bidders are risk seeking, uniform price may be better for the auctioneer.

On the one hand, carbon auction is still in its infancy, related data are scarce; on the other hand, carbon auction is the game between bidders and government, and among bidders themselves, which is also a source of complexity of the energy system [19]. Traditional economic analysis and intelligent simulation cannot describe human psychology effectively. To bridge this gap, this paper studies the above issues in a non-theoretical way, or by purely experimental means. The experimental platform is programmed by z-Tree software [20].

3. Experimental design

3.1. Participants

In each experiment, twelve participants were selected randomly from the Beijing Institute of Technology. The ratio of males to females was roughly one. Participants were between 20 and 25 years old, all voluntary. Each participant was given the role of a power plant with multiple generation units to produce electricity to be sold at a known price. The experiments were run entirely by computerized means, with participants sitting in the same room, in front of terminals isolated by partitions. At the end of the experiments, their earnings were converted into Chinese dollars (RMB Yuan). Overall, participants spent about 180 min in the lab and earned on average 50 RMB Yuan in one session.

Table 1
Standard auction types.

Static (sealed) auction			Dynamic (clock) auction	
Uniform price auction (adopted by most EU countries currently)	Discriminatory price auction	Second price auction	Ascending auction (English auction)	Descending auction (Dutch auction)

3.2. Pretreatment

As previously mentioned, the risk preference measurement is a good benchmark to compare this paper's results with other papers'. Participants' risk preferences were measured by the following two questions. Question 1 tested participants' risk preferences within the earnings framework, while Question 2 tested them within the loss framework.

(1) If business A can win 800 Yuan certainly, while business B can win 1000 Yuan with possibility of 85% or win nothing with possibility of 15%, what will be your choice?
(2) If business A can lose 800 Yuan certainly, while business B can lose 1000 Yuan with possibility of 85% or lose nothing with possibility of 15%, what will be your choice?

The two questions above were from Kahneman and Tversky's experiments of "certainty effect" and "reflection effect" [21]. Their experiment results based on US participants showed that within the earnings framework, about 84% participants chose A, which means they were risk averse. Within the loss framework, about 87% participants chose B, which means they were risk seekers.

By means of this pretreatment, it was found that on average, within the earnings framework, 91.6% participants chose A, while within the loss framework, 91.8% participants chose B. Compared with Kahneman and Tversky's experimental results, this experiment's participants showed a smaller risk preference within the earnings framework and a larger risk preference within the loss framework.

3.3. Experiment design

In the experiment, subjects represented participants' private variables. Unit generation cost is represented as cost. Carbon emissions needed for unit electricity are denoted as *CarbonNeed*, whose numerical values roughly reflect the difference between fuel cost of gas power plant and coal power plant (Table 2). *Globals* represent global variables, including total emission allowances to be auctioned (*Carbon_quantity*), electricity price (*Electricity_price*), reserve price (*ReservePrice*) and penalty price (*Punish*). Treatments represent the three stages of the process of the experiment: (1) input stage; (2) market clearing stage, and (3) results showing stage. Here private value is the maximum price the agent would pay for unit allowance. Private values of coal power plant and gas power plant are assumed roughly equal, which avoids unfair competition in the market.

3.4. Scenario design and performance measures

3.4.1. Scenario design

Options involved in this experiment included: auction formats, the possibility of communication (face to face) between bidders, banking and the penalty price. Assigning value to each option, a four-dimensional scenario space was formed.

3.4.1.1. Auction formats. In EU ETS, two types of auctions often considered are static sealed-bid auction and dynamic ascending auction. The main difference between these two auctions is the rounds. There is only one round in static auction while many rounds take place in dynamic auction. Considering the simplicity of static auction, all countries chose static auction, among which Hungary, Ireland and Lithuania use a sealed uniform price auction. Therefore, uniform price auction, discriminatory price auction and ascending clock auction are examined here.

3.4.1.2. The possibility of communication between bidders. Here, two options were set: (1) Low communication possibilities. Bidders were not allowed to communicate each other explicitly. Their generation costs were generated randomly again in each round. (2) High communication possibilities. The number of bidders was halved to six and their costs kept constant in each round, which would facilitate the explicit collusion. Here the aim is to distinguish the impact of tacit and explicit collusion on auction results.

3.4.1.3. Banking. Here two options were set: (1) No banking. (2) Banking. Here the aim is to examine whether banking is conducive to emissions reduction.

3.4.1.4. Penalty price. Here two options were set: (1) Low penalty price (Punish = 40). (2) High penalty price (Punish = 80). Here we want to examine the impact of different penalty prices on auction results when banking is allowed.

Therefore, the whole scenario space has four dimensions, including twenty-four scenario combinations.

3.4.2. Performance measures

Here auction efficiency [9], demand withholding and volatility of electricity supply were used as performance measures.

Table 2
The experiment environment.

Subjects
Gas power plant: $\cos t \sim U(70, 90)$ (here U represents a uniform distribution), $CarbonNeed = 1$; coal power plant: $\cos t \sim U(30, 50)$, $CarbonNeed = 2$

Globals
$Carbon\_quantity$; $Electricity\_price = 120$; $ReservePrice = 20$; $Punish$

Treatments
Stage 1: Input stage
Variables showed:
Maximum production of electricity: $Capacity = 50$; Cost of generation: $\text{cost}_{\text{coal power plant}} = 70 + 20 \times U(0, 1)$, $\text{cost}_{\text{gas power plant}} = 30 + 20 \times U(0, 1)$; $Electricity\_price = 120$; Private value:
$PrivateValue = (Electricity\_price - cost)/(Carbon\_Need)$
Variables inputted:
Bid price: *Price*, bid quantity: *Quantity*, electricity actually produced: *elec*

Stage 2: Market clearing stage
Set carbon allowances obtained by each bidder and the price, calculate bidders' profit according to different auction formats (including discriminatory price auction, uniform price auction and ascending clock auction) [17]. Then, bidders' profits are calculated as the difference between their revenue from electricity and their costs of generation and carbon allowances.

Stage 3: Result showing stage
Variables showed:
Allowance get in this period: *Carbon_get*, profit: *profit*, price paid: *realprice*
($profit = elec \times (Electricity\_price - \cos t) - Carbon\_get \times realprice - punish \cos t$)

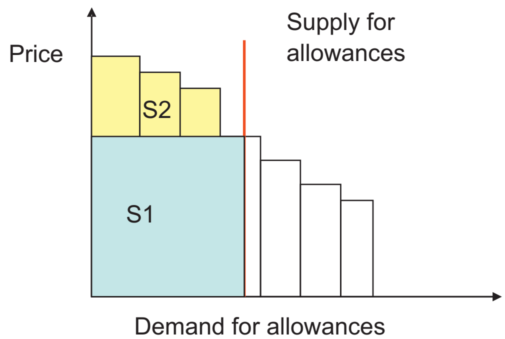

Fig. 1. Supply and demand relationship of carbon allowance auction in the uniform price auction.

Auction efficiency is calculated as the actual value achieved as a percentage of the maximum possible value (Burtraw et al.) [10], which can de defined as follows:

$$eff_i = \frac{S1}{(S1 + S2)}$$

In the equation above, *eff* stands for auction efficiency, *i* refers to the three types of auctions, *S1* is government earnings from auction, and *S2* is bidders' profit, as shown in Fig. 1.

A significant feature of carbon auction is that the government can punish enterprises for excess emissions. Therefore, the traditional auction efficiency was extended as follows:

$$eff_i = \frac{actp_i}{\max p_i} = \frac{gov_i}{(gov_i + tp_i)} \quad (1)$$

In the equation above, *actp* refers to government's actual earnings from auction, *max p* refers to government's maximum earnings from auction in theory. *gov* is actual government earnings from auction and punishment, *tp* is total bidders' profit. *i* refers to the three types of auctions.

Demand withholding (*desh*) can be defined as the difference between bidders' maximum capacity (*capacity*) and bidders actual output (*elec*), as follows:

$$desh_i = \sum_{j=1}^{12} (capacity_j - elec_j) \quad (2)$$

Different from existing literature, this paper considered the impact of carbon auction on actual output. Here the coefficient of standard deviation of electricity supply (vol_i) was used as the third performance measure, which can be defined as follows:

$$vol_i = \frac{sd_i}{\text{mean}_i}$$

In the equation above, *sd* is the standard deviation of total electricity output, and mean is the mean value of total electricity output.

4. Experiment results

Though there were twenty-four scenario combinations, this paper mainly considered three integrated settings, as shown in Table 3 (Burtraw et al.) [10].

4.1. Comparison of the three allowance auction formats in the baseline scenario

This section examines the rank order of the three auction formats; e.g., which auction format has better performance in the baseline scenario. Firstly, we examine allowance prices in three auction formats, as shown in Fig. 2.

Table 3
Combinations of settings and auction mechanisms considered.

Baseline scenario (compare auction formats)	Richer scenario 1 (compare tacit and explicit collusion)	Richer scenario 2 (examine banking and penalty price)
No communication 12 bidders 540 permits Rerandomize costs No banking Low penalty price	Communication 6 bidders 270 permits Same costs No banking Low penalty price	No communication 12 bidders 540 permits Rerandomize costs Banking Low penalty price High penalty price
8 auctions per session Uniform (100 sessions) Discriminatory (100 sessions) Clock (100 sessions)	8 auctions per session Uniform (100 sessions) Discriminatory (100 sessions) Clock (100 sessions)	8 auctions per session Uniform (100 sessions) Discriminatory (100 sessions)

Here mean values of 100 sessions were used to analyze each auction, which eliminates the influence of randomness to some extent.

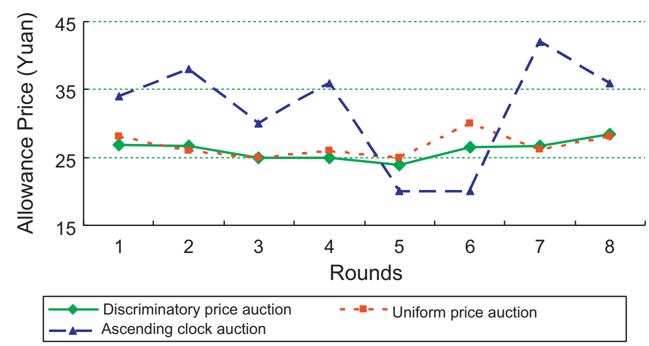

Fig. 2. Allowance prices under three auction formats in the baseline scenario.

Table 4
Friedman test on allowance prices (baseline scenario).

	Mean ranks
Discriminatory auction	1.63
Uniform auction	1.88
Ascending clock auction	2.5

It can be seen from Fig. 2 that compared with ascending clock auction, discriminatory price auction and uniform price auction show a similar trend of carbon allowance price. In ascending clock auction, allowance price was high in the first few rounds and low in Rounds 5 and 6. This may be because there was tacit collusion among bidders, to some extent, in these rounds. In the last two rounds, the collusion between bidders collapsed, which pushed up the allowance price. We did a nonparametric Friedman test on allowance prices of discriminatory auction, uniform auction and ascending clock auction (Tables 4 and 5).

It can be seen from the significance level (as shown in Table 5, Sig = 0.197) that there was not significant difference between allowance prices under the three auctions. Therefore, we can conclude that from the perspective of maximizing allowance price, no auction format shows a significant advantage over others. Meanwhile, there is unstable tacit collusion between bidders in the clock

Table 5
Test statistics of allowance prices (baseline scenario).[a]

N	8
Chi-square	3.25
df	2
Asymp. Sig.	0.197

[a] Friedmans test.

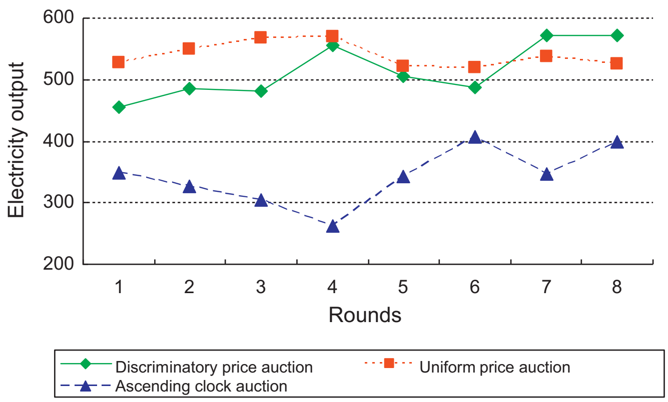

Fig. 3. Electricity supplies under three auction formats.

Table 6
Electricity supplies in three auction formats.

	Discriminatory price auction	Uniform price auction	Ascending clock auction
Standard deviation	45.35	20.36	46.93
Mean	514.38	539.88	342.25
Coefficient of variation	0.09	0.04	0.14

auction. At the end of auction, the collusion has the possibility of collapsing.

Next, we examine electricity supply in the three auction formats.

It can be seen from Fig. 3 that because of the high allowance price, electricity supply in ascending clock auction was the least. Compared with discriminatory price auction, supply in uniform price was relatively higher. Electricity supply volatility (Table 6) in ascending clock auction was the largest, while it was the least in uniform price auction. Therefore, from the perspective of ensuring electricity supply, uniform price auction is better than discriminatory price auction and ascending clock auction.

Thirdly, demand withholding by bidders in the three auction formats was examined. Demand withholding is another form of tacit collusion between bidders, in addition to price. Larger demand withholding means the auction cannot discover real demand of bidders effectively.

It can be seen from Fig. 4 that there were large differences between bidders' demand withholding in the three auction formats. Demand withholding in ascending clock auction was the largest (405 on average). A nonparametric Wilcoxon signed ranks test was done on demand withholding under discriminatory price auction and uniform price auction. Results are shown in Tables 7–9.

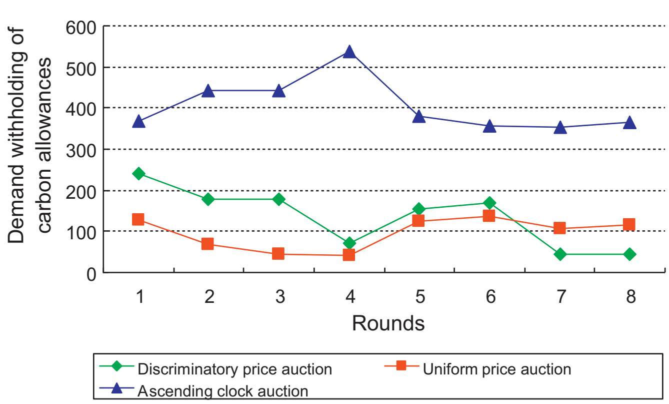

Fig. 4. Demand withholding of bidders in three auction formats.

Table 7
Demand withholding.

	Mean value	Standard variance
Discriminatory price auction	134.38	72.54
Uniform price auction	96.00	38.89
Ascending clock auction	405.75	64.37

Table 8
Wilcoxon signed ranks test on demand withholding (baseline scenario).

		N	Mean rank	Sum of ranks
Uniform auction – discriminatory auction	Negative ranks	2[a]	4.5	9
	Positive ranks	6[b]	4.5	27
	Ties	0[c]		
	Total	8		

[a] Uniform auction < discriminatory auction.
[b] Uniform auction > discriminatory auction.
[c] Uniform auction = discriminatory auction.

It can be seen in Table 7 that both mean values and standard variance of discriminatory price auction were larger than in uniform price auction. We further did a nonparametric Wilcoxon signed ranks test (as shown in Tables 8 and 9) and found that there was no significant difference between demand withholdings under discriminatory price auction and uniform price auction (Sig = 0.208). We also did a nonparametric Wilcoxon signed ranks test on demand withholdings under uniform price auction and ascending clock auction and found that there was a significant difference (Sig = 0.012, as shown in Tables A.1 and A.2) between them.

Thus it can be concluded that demand withholding in ascending clock auction format was larger than in the other two auction formats. Volatility of demand withholding in discriminatory price auction was larger than in uniform price auction, but there was no significant difference in mean values of these two auction formats. This may be because bidders in uniform price auction know allowance price at the end of each round, which makes them have more accurate expectations and reduces the volatility of their demand withholdings.

At last, auction efficiencies of the three auction formats were examined.

It can be seen in Fig. 5 that on average, auction efficiency in ascending clock auction was the highest, while in discriminatory price auction it was the lowest.

Auction efficiencies of ascending clock auction were very high in some rounds (such as Rounds 2 and 7). But in some rounds (such as Rounds 5 and 6) efficiency was only about 52%. In ascending clock auction, bidders made decisions only on one-dimension, so they found it easier to reach tacit collusion [10]. But the collusion is unstable. As the auction drew to a close, the collusion failed. On the whole, ascending clock auction can help government discover bidders' private values effectively in the baseline scenario.

Auction efficiencies of the three auctions did not differ much. We did a nonparametric Friedman test on them. Results are shown in Tables 10 and 11.

It can be seen in Table 11 that there was a weak significant difference between values of three auction formats (Sig = 0.097). Therefore, we can conclude that from the perspective of auction

Table 9
Test statistics of demand withholding (baseline scenario).[b]

	Uniform auction – discriminatory auction
Z	−1.26[a]
Asymp. Sig. (2-tailed)	0.208

[a] Based on negative ranks.
[b] Wilcoxon signed ranks test.

Fig. 5. Auction efficiencies in three auction formats.

Table 10
Friedman test on auction efficiencies (baseline scenario).

	Mean rank
Discriminatory auction	1.44
Uniform auction	2.11
Ascending clock auction	2.44

Table 11
Test statistics of auction efficiencies (baseline scenario).[a]

N	8
Chi-square	4.667
df	2
Asymp. Sig.	0.097

[a] Friedmans test.

efficiency, although there may be obvious collusion during the auction, clock auction has better performance than the other two auction formats.

4.2. Comparison of three auction formats when communication is allowed (Richer scenario 1)

In this section, the number of bidders was halved into six to examine the impact of tacit collusion between bidders on auction performances. The number of bidding coal power plants and gas power plants was equal. Their unit generation cost kept constant in each round. In this scenario, there was high possibility of communication (it was allowed), banking was not allowed and penalty price was set at 40.

Firstly, allowance prices in the three auction formats were examined. Results are shown in Fig. 6.

It can be seen from Fig. 6 that when communication between bidders was allowed, allowance price of discriminatory price auction was larger than the other two auction formats most of the times (Sig = 0.02, as shown in Tables A.3 and A.4).

It can be seen in Table 12 that mean values of allowance prices under uniform price auction were between prices under the other

Table 12
Descriptive statistics of carbon allowance price (Richer scenario 1).

	Maximum	Minimum	Means	Standard deviation
Uniform price auction	36	15	28.275	7.245
Discriminatory price auction	38.4	30.94	35.44	2.643
Ascending clock auction	26	20	21.5	2.07

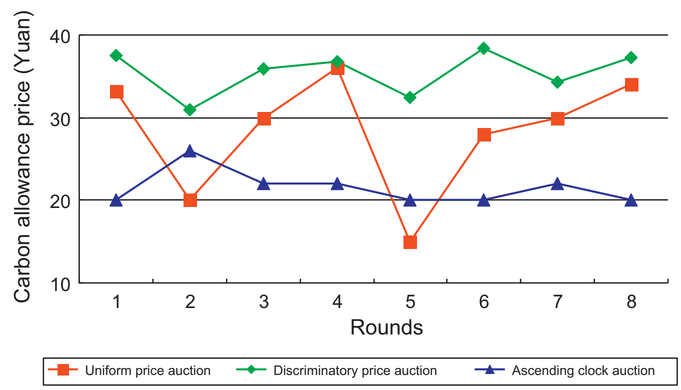

Fig. 6. Carbon allowance prices under three auction formats when communication was allowed.

two auction formats, and volatility was the highest (7.245). This means that compared with mean values of allowance prices in baseline scenario, when bidders are fewer and communication between them is allowed, discriminatory price auction can prevent collusion effectively, while ascending clock is conducive to explicit collusion.

Next, electricity supplies in the three auction formats were examined.

It can be seen from Fig. 7 that as different from baseline scenario, when communication between bidders was allowed, although allowance price in clock auction was relatively low, electricity supply was also relatively low. This may be because explicit collusion

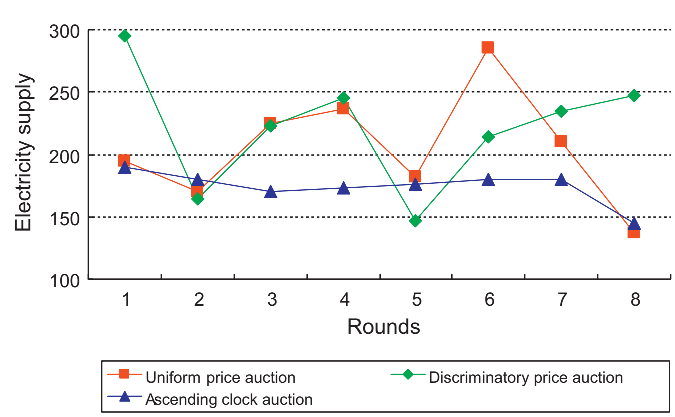

Fig. 7. Electricity supplies under three auction formats when communication was allowed.

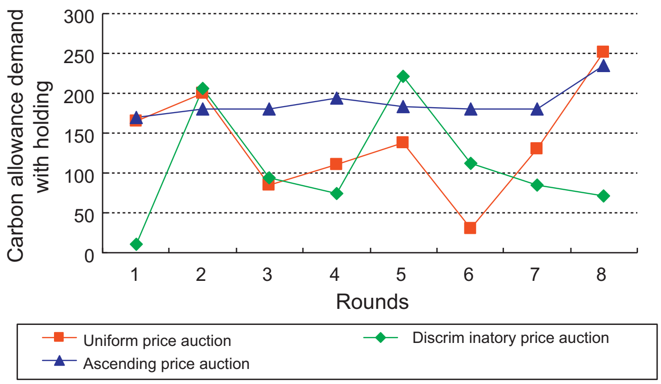

Fig. 8. Demand withholdings under three auction formats when communication was allowed.

Table 13
Descriptive statistics of electricity supplies (Richer scenario 1).

	Discriminatory price auction	Uniform price auction	Ascending clock auction
Standard deviation	205.13	221.25	174.25
Mean	45.24	47.36	13.23
Coefficient of variation	0.22	0.21	0.08

enables bidders to reduce their electricity supplies to pull down the allowance price. In contrast, electricity supplies in discriminatory price auction and uniform price auction were relatively larger. As seen in Table 13, volatility of electricity supplies in ascending clock auction was less than in the other two auction formats, which means relatively stable supply alliance among bidders under ascending clock auction. So we can conclude that from the perspective of ensuring electricity supply, performance of ascending clock auction is worse than the other two auction formats.

Thirdly, we examine demand withholdings in the three auction formats when communication is allowed.

It can be seen from Fig. 8 that when communication was allowed, demand withholding in ascending clock auction was larger than in the other two auction formats, on average.

It can be seen from Table 14 that volatility of demand withholding in ascending clock auction was much less than in the other two auctions when communication was allowed, implying that bidders in ascending clock auction tend to withhold their real demand to pull down allowance price collectively. This coalition for demand withholding was more stable in ascending clock auction.

Finally, we examined efficiencies of the three auction formats.

Table 14
Demand withholdings in three auction formats when communication was allowed.

	Mean	Standard deviation
Uniform price auction	138.75	68.25
Discriminatory price auction	109.25	70.88
Ascending clock auction	187.88	20.15

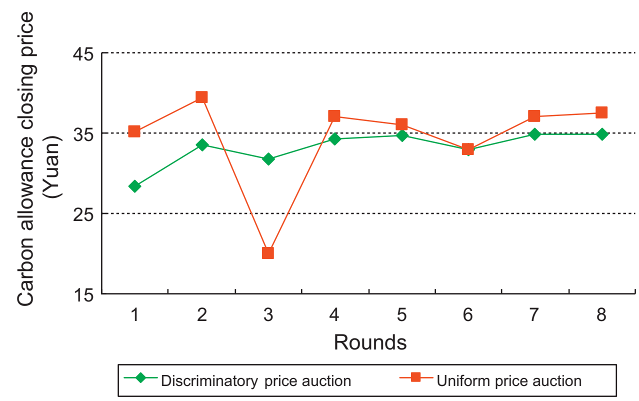

Fig. 10. Carbon allowance prices under two auction formats when banking was allowed (low penalty price).

It can be seen from Fig. 9 that when communication was allowed, efficiency of discriminatory price auction was the highest (94.6%) while in ascending clock auction it was the lowest (54.7%) (Sig = 0.02, as shown in Tables A.5 and A.6). Therefore, we can conclude that when there are few bidders and communication between them is allowed, ascending clock auction is conducive to bidders' alliance. In contrast, discriminatory price auction can effectively prevent explicit collusion. In terms of auction efficiency, discriminatory price has a better performance than the other two auctions in this scenario.

4.3. Comparison of two auction formats considering banking and penalty price (Richer scenario 2)

Because there may be explicit collusion between some bidders in ascending clock auction, it is not a good option for China's electricity market as it still has only limited competition. Next, we focus on discriminatory price auction and uniform price auction. An important feature of carbon allowance is banking, which can help bidders optimize their bidding behaviors. Here we set two options: (1) low penalty price (penalty price = 40); (2) high penalty price (penalty price = 80). There were twelve participants, six of whom

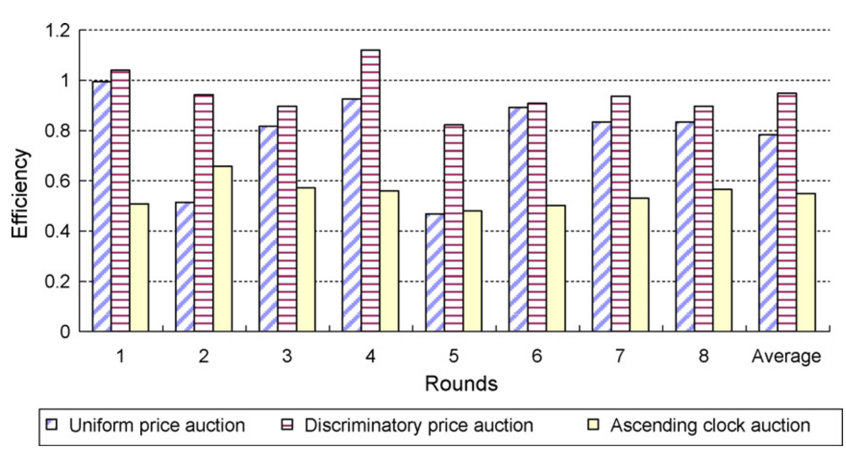

Fig. 9. Efficiencies of three auction formats when communication was allowed.

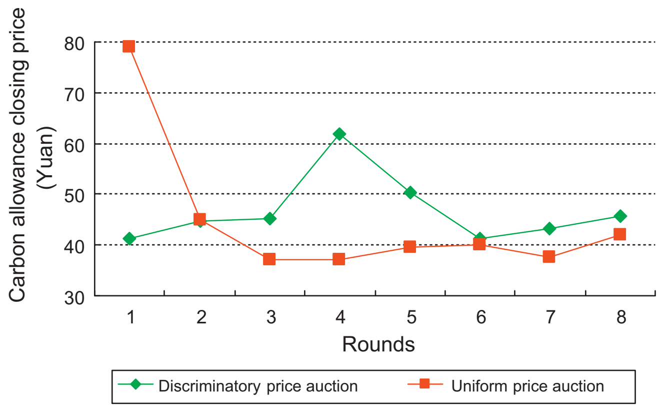

Fig. 11. Carbon allowance prices under two auction formats when banking was allowed (high penalty price).

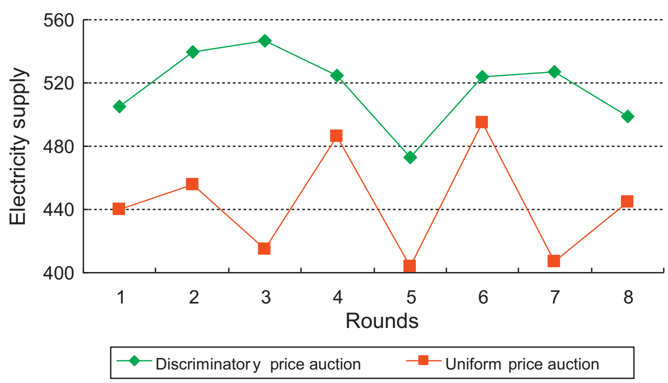

Fig. 12. Electricity supplies under two auction formats when banking was allowed (low penalty price).

were coal power plants and the other six were gas power plants. Scenario was set as low possibility of communication; banking was allowed.

We examine the impact of banking on allowance prices and electricity supplies, as follows (Due to the limited space, statistical results are omitted here).

It can be seen from Fig. 10 that in the case of low penalty price, banking may cause bidders to indulge in speculation to a certain extent and exacerbate market volatility.

It can be seen from Fig. 11 that when penalty price was increased from 40 to 80, the market was in panic. Volatilities and mean values of allowance prices in the scenario of high penalty price were larger than in the scenario of low penalty price.

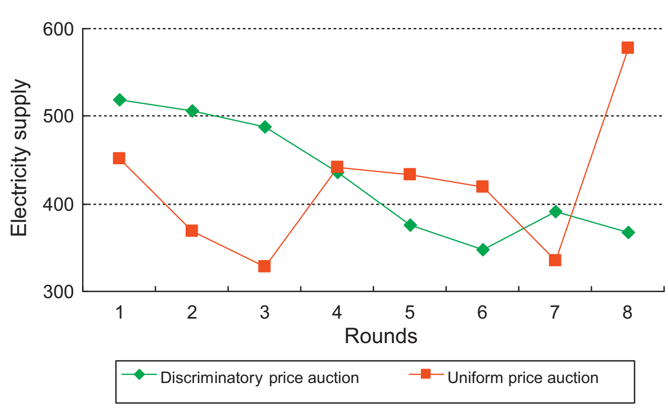

Fig. 13. Electricity supplies under two auction formats when banking was allowed (high penalty price).

It can be seen from Fig. 12 that when banking is allowed, though there is speculation, electricity supplies may be decreased due to uncertainties about the future.

It can be seen from Fig. 13 that when banking was allowed and penalty price was doubled, bidders' electricity supplies significantly decreased. Bidders' production tended to be conservative. At the same time, volatilities of electricity supplies increased, which means high penalty price may exacerbate panic in the market.

5. Conclusions

With further development of the carbon market, free distribution of carbon allowance is likely to be replaced by auction to a certain extent. The choice of specific carbon allowance auction formats is a very complex issue. On one hand, auction should minimize tacit or explicit collusion between bidders, improving auction efficiency. On the other hand, auction should reduce the impact (of environmental regulations) on relevant industries and the macro economy. In extant literature, some authors have reported different results based on their experiment settings but have not given a comparable basis. This paper has tried to integrate them in a comprehensive framework and tried to explain different results in the context of bidders' risk attitudes.

Based on analysis of current EU ETS allowance auction, this paper compares three auction formats (discriminatory price auction, uniform price auction and ascending clock auction) using an experimental method. Through the analysis of experimental results, we can conclude as follows:

(1) When there are more bidders and there is no communication between them, there may be unstable tacit collusion between bidders in case of ascending clock auction. From the perspective of ensuring electricity supplies, uniform price auction has better performance. This may be because in uniform price auction, bidders know market clearing price after each round and have clearer expectations on future price trend, which reduces volatility of their demand withholdings. Although there may be obvious collusion in the midst of the auction process, efficiency of the clock auction format is higher than the other two auction formats, which is different from Burtraw et al. [10] This may be related to bidders' risk attitudes. When bidders have a smaller risk preference within the earnings framework, they may not collude for fear of losing revenue.
(2) When there are fewer bidders and communication is allowed, carbon allowance price in discriminatory price auction was the highest, while it was the lowest in ascending clock price auction. This means discriminatory price auction can prevent collusion effectively, while ascending clock auction is conducive to bidders' collusion.
(3) When communication is allowed, allowance price in clock auction is low but electricity supplies are also relatively less. This is because collusion between bidders reduces supplies to drive down allowance price. Volatility of electricity supplies in clock auction was less than in the other two auctions, which means there may be relatively stable supply under clock auction.
(4) In the scenario of low penalty price, banking increases allowance price fluctuations. This means banking causes bidders' speculation to a certain extent and exacerbates market volatility, which is different from existing literature where the view is that allowance banking helps smooth price variability [4]. When the penalty price is increased, mean values and volatility of allowance price also increase, resulting in electricity supplies decreasing significantly and volatility being increased. Bidders' production tends to be conservative. High penalty price exacerbates the market shock.

This paper does not consider the secondary market. We also did not invite real China's power plants' decision makers to participate in experiments. There are left for future research.

Appendix A.

Table A.1
Wilcoxon signed ranks test on demand withholding (baseline scenario).

		N	Mean rank	Sum of ranks
Ascending clock auction – uniform auction	Negative ranks	0[a]	0	0
	Positive ranks	8[b]	4.5	36
	Ties	0[c]		
	Total	8		

[a] Uniform auction < discriminatory auction.
[b] Uniform auction > discriminatory auction.
[c] Uniform auction = discriminatory auction.

Table A.2
Test statistics of demand withholding (baseline scenario).[b]

	Ascending clock auction – uniform auction
Z	−2.521[a]
Asymp. Sig. (2-tailed)	0.012

[a] Based on negative ranks.
[b] Wilcoxon signed ranks test.

Table A.3
Friedman test on allowance price (Richer scenario 1).

	Mean rank
Uniform auction	1.75
Discriminatory auction	3
Ascending clock auction	1.25

Table A.4
Test statistics of allowance price (Richer scenario 1).[a]

N	8
Chi-square	13
df	2
Asymp. Sig.	0.002

[a] Friedmans test.

Table A.5
Friedman test on auction efficiencies (Richer scenario 1).

	Mean rank
Uniform auction	1.75
Discriminatory auction	3
Ascending clock auction	1.25

Table A.6
Test statistics of auction efficiencies (Richer scenario 1).[a]

N	8
Chi-square	13
df	2
Asymp. Sig.	0.002

[a] Friedmans test.

References

[1] Svendsen GT, Vesterdal M. How to design greenhouse gas trading in the EU? Energy Policy 2003;31(14):1531–9.
[2] Lu W, Cui LQ. The analysis of initial allocation modes of tradable emission rights. China Environmental Management 2003;22(5):8–9 [in Chinese].
[3] Parry IWH, Williams IRC, Goulder LH. When can carbon abatement policies increase welfare? The fundamental role of distorted factor markets. Journal of Environmental and Economics Management 1999;37(1):52–84.
[4] Cason TN, Gangadharan L. Emissions variability in tradable permit markets with imperfect enforcement and banking. Journal of Economics Behavior and Organization 2006;61(2):199–216.
[5] Klemperer P. What really matters in auction design. Journal of Economic Perspectives 2002;16:169–89.
[6] Wang JJD, Zender JF. Auctioning divisible goods. Economics Theory 2002;19:673–705.
[7] Porter D, Vragov R. An experimental examination of demand reduction in multi-unit versions of the uniform-price: Vickrey, and English auctions. Managerial and Decision Economics 2006;27(6):445–58.
[8] Pekec AS, Tsetlin I. Revenue ranking of discriminatory and uniform auctions with an unknown number of bidders. Management Science 2008;54(9):1610–23.
[9] Alsemgeest P, Noussair C, Olson M. Experimental comparisons of auctions under single- and multiunit demand. Economic Inquiry 1998;36(1):87–97.
[10] Burtraw D, Goeree J, Holt CA, Myers E, Palmer K, Shobe W. Collusion in auctions for emission permits. Jounal of Policy Analysis and Management 2009;28:672–91.
[11] Goeree JK, Offerman T, Sloof R. Demand reduction and preemptive bidding in multi-unit license auctions. CalTech 2006.
[12] Katok E, Roth AE. Auctions of homogeneous goods with increasing returns: experimental comparison of alternative Dutch auctions. Management Science 2004;50(8):1044–63.
[13] Kling C, Rubin J. Bankable permits for the control of environmental pollution. Journal of Environmental Economics and Management 1997;65:101–15.
[14] Cronshaw M, Brown KJ. An experimental analysis of emissions permits with banking and the clean air act amendments of 1990. Research in Experimental Economics 1999;7:1–24.
[15] Godby RW, Mestelman S, Muller RA, Welland JD. Emissions trading with shares and coupons when control over discharges is uncertain. Journal of Environmental Economics and Management 1997;32(3):359–81.
[16] Mestelman S, Moir R, Muller RA. A laboratory test of a Canadian proposal for an emissions trading program. Research in Experimental Economics 1999;1:45–92.
[17] Cong RG, Wei YM. Auction design for the allocation of carbon emission allowances: uniform or discriminatory price? International Journal of Energy and Environment 2010;1(3):533–46.
[18] Chen SG, An Y, Zhao LX. The comparison of auction mechanisms based on agents' risk attitudes. Forecasting 2004;23(5):65–7 [in Chinese].
[19] Ohta T. Energy systems and adaptive complexity. Applied Energy 2000;67:3–16.
[20] Fischbacher U. z-Tree: Zurich toolbox for ready-made economic experiments. Experimental Economics 2007;10(2):171–8.
[21] Kahneman D, Tversky A. Prospect theory: an analysis of decision under risk. Econometrica 1979;47(2):263–92.